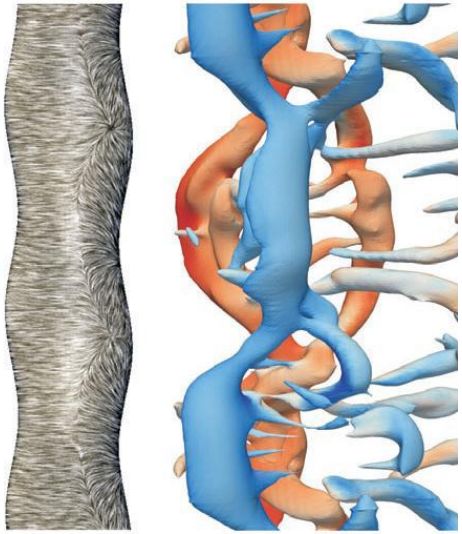
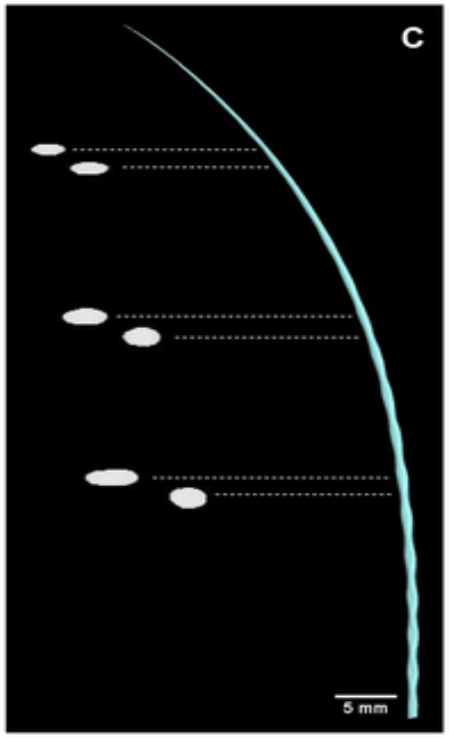
How seal whiskers suppress vortex structures:

Effects of the twisting angles

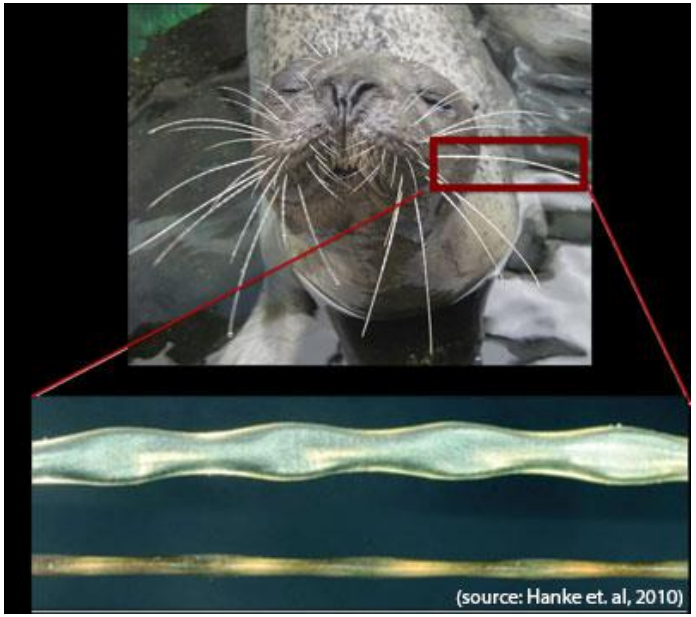




Aidan Rinehart, Vikram Shyam, Wei Zhang

Cleveland State University and NASA GRC

Seal and their whiskers…



Hanke et al. 2010

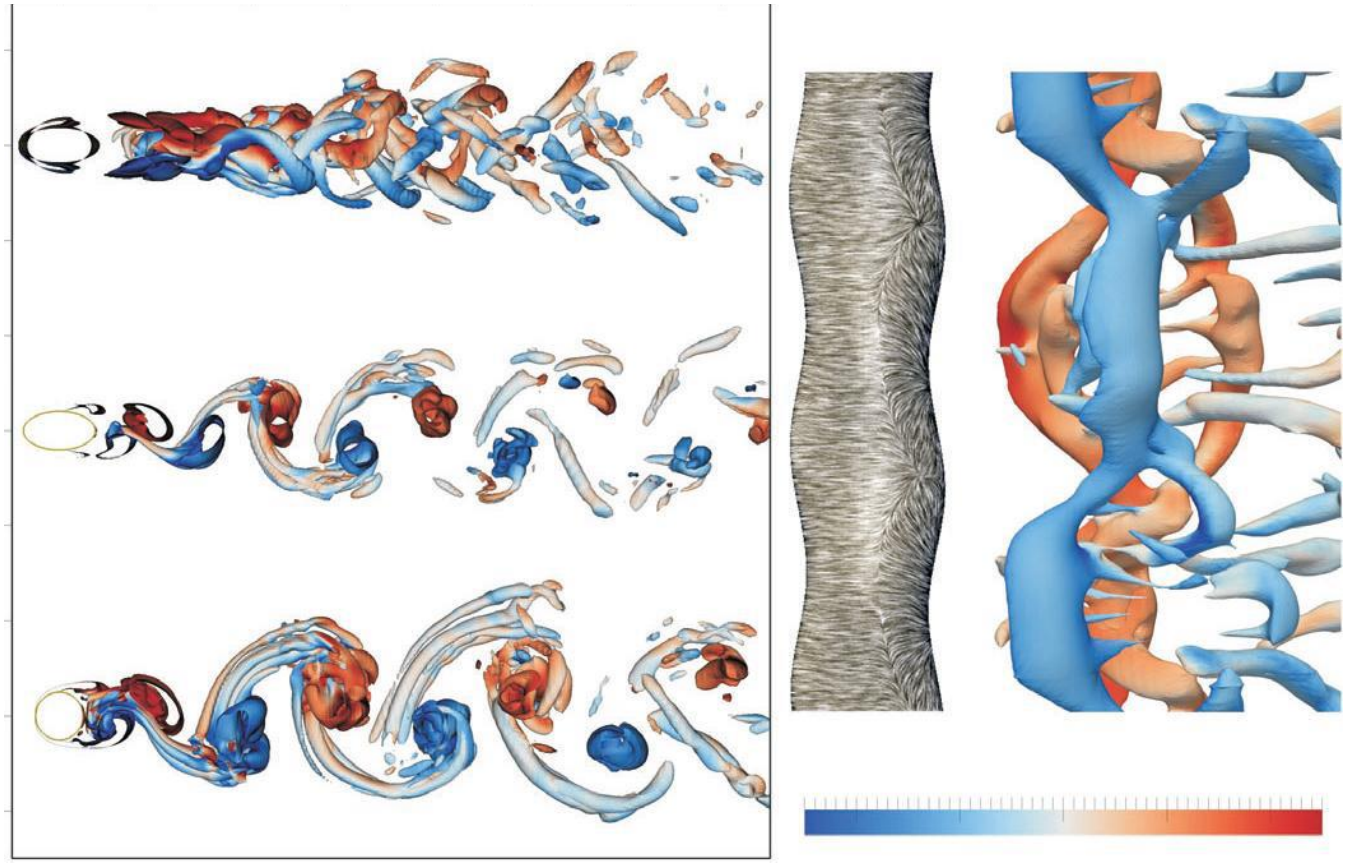
Montgomery et al, 1995

Wake behind a seal whisker

Seal whisker

Ellipse

Cylinder



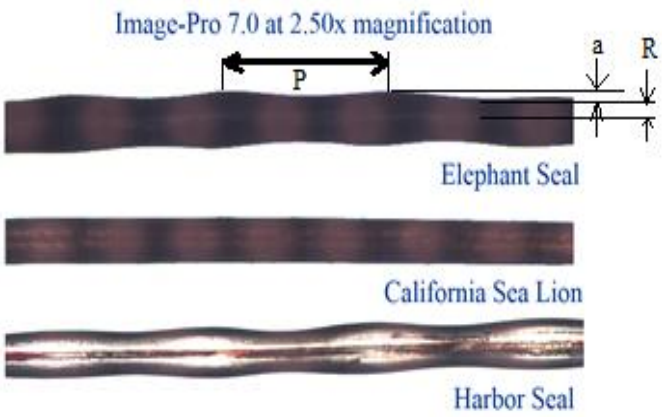
Re = 500

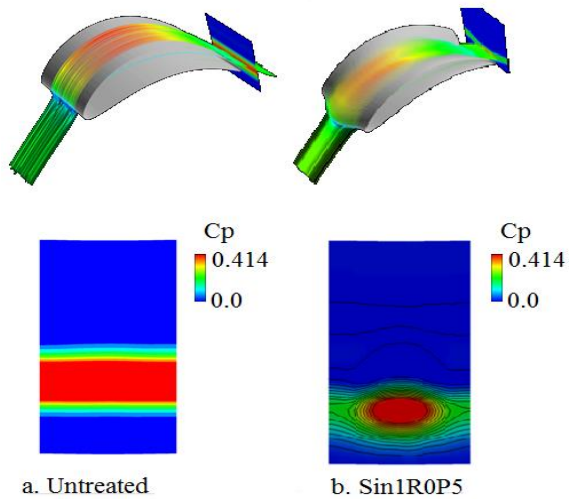
Witte et al. 2012.

- *Re-organize* the vortex structures
- Push vortices *away* from the body

Seal whisker inspired design

- *Passive flow control strategy – from whiskers to turbine blades*

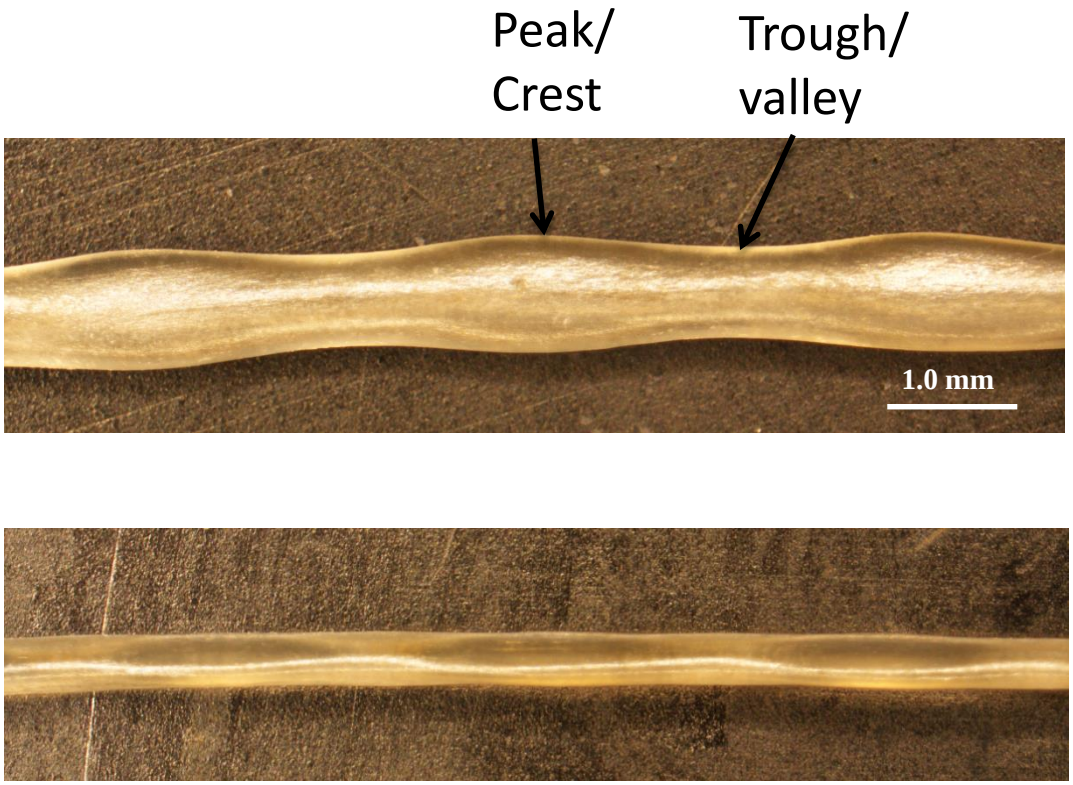




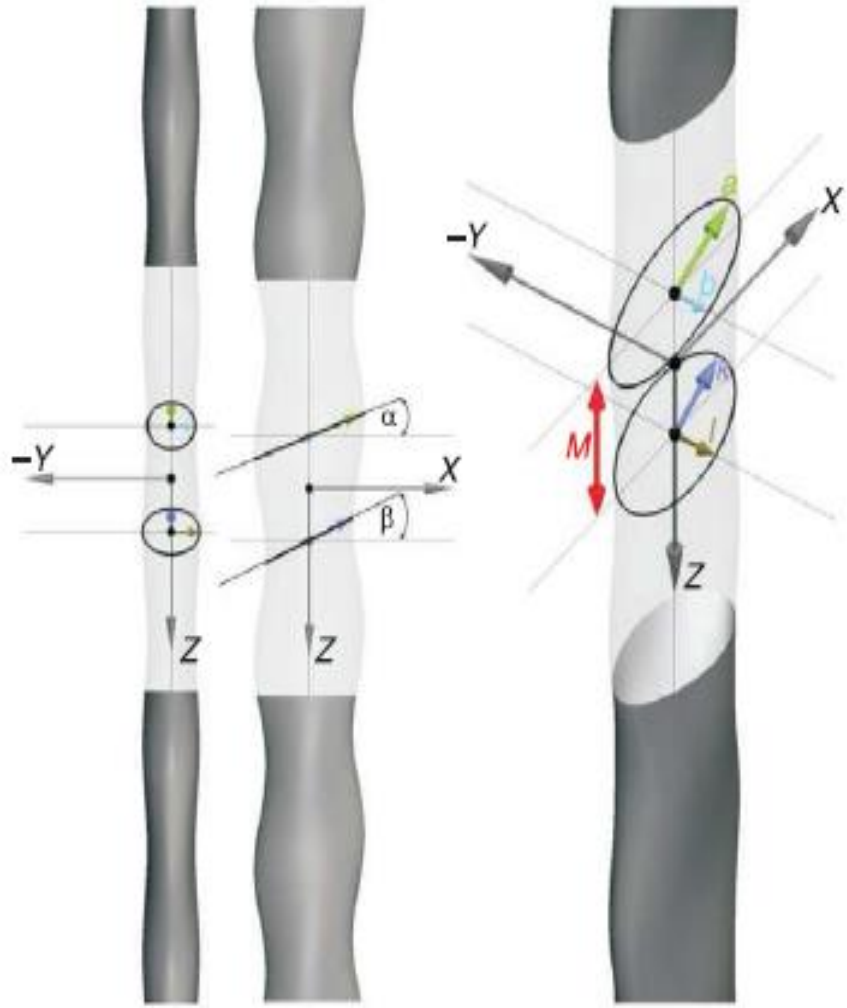
Seal whiskers | Turbine seal blade | Wavy wind-turbine tower?

- *Flow sensor for underwater applications (Beam 2015)*

Seal whisker surface morphology

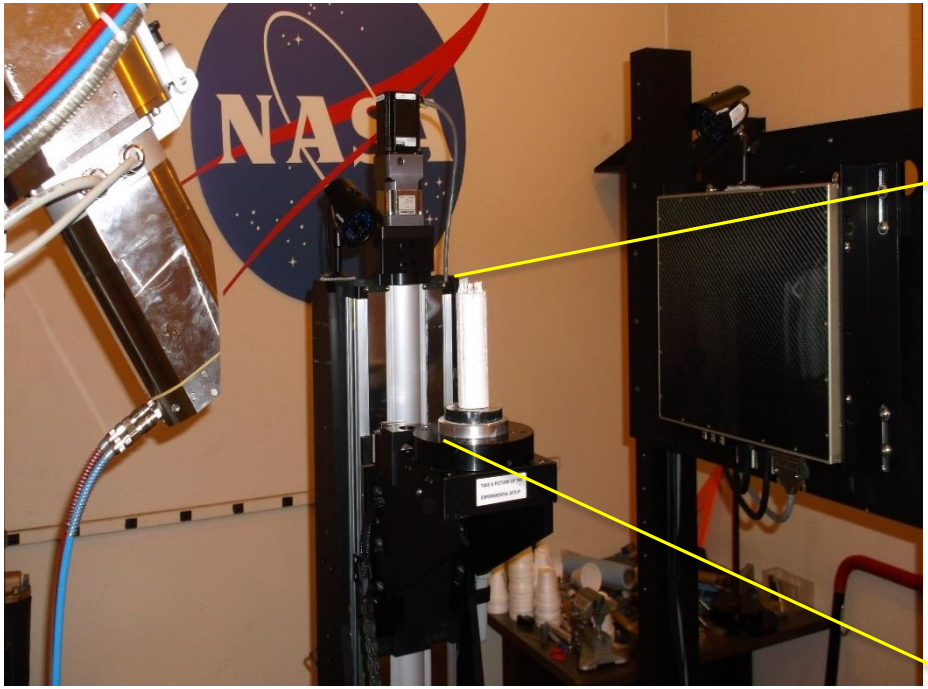


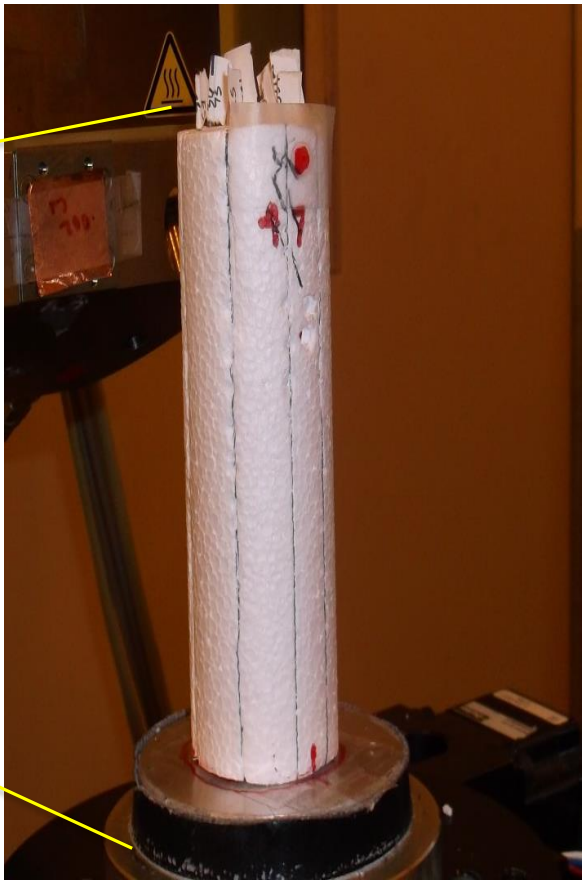
Harbor Seal Whiskers



Hanke et al. 2010. *Journal of Experimental Biology*, Vol 213, pp. 2665-2672.

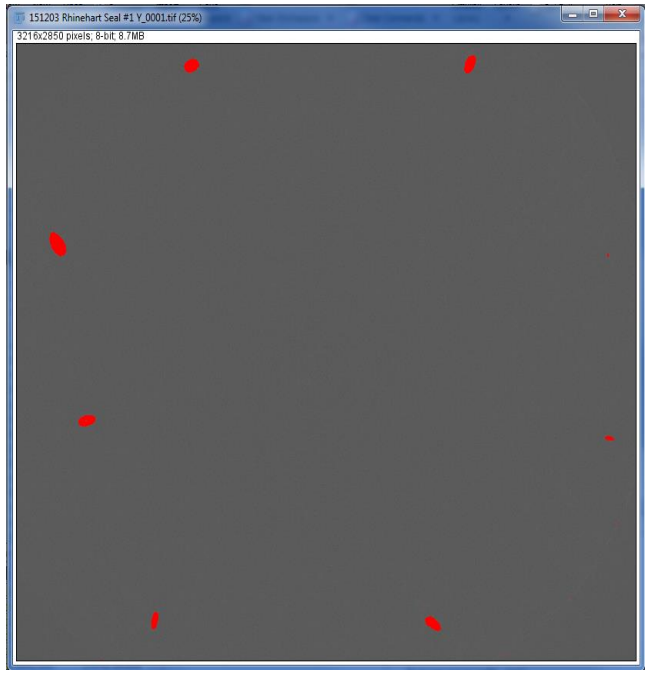
CT scanning of the whisker samples



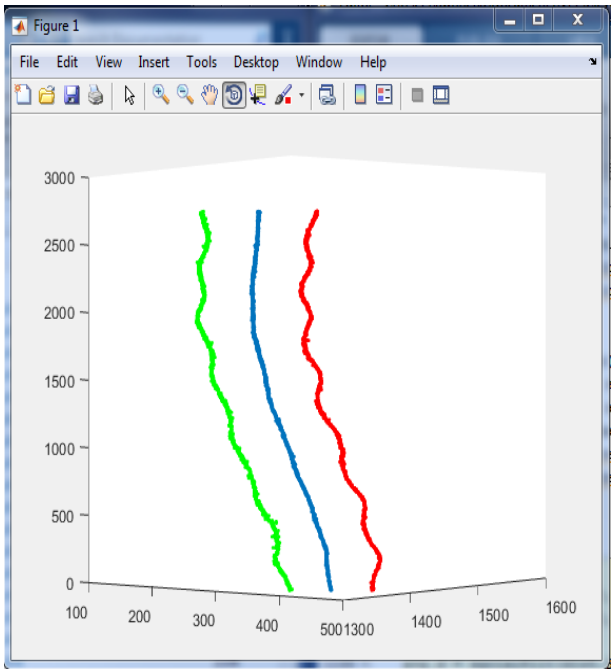


- Whiskers mounted in styrofoam (27 samples)
- Mount positioned on rotating plate between x-ray emitter and detection panel
- Density captured in images relating to volume slices
- Spatial resolution: voxel size 4-10.5 μm^3

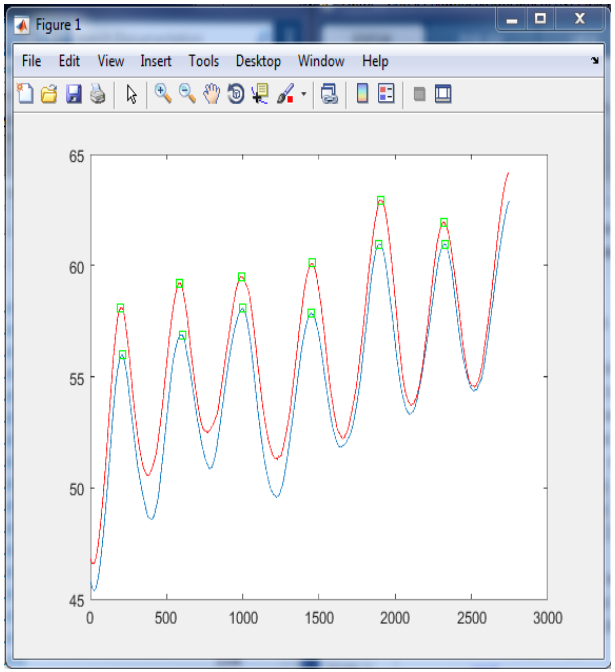
Reconstruction of whisker surface morphology



Edge detection of a cross-section from CT scanning data



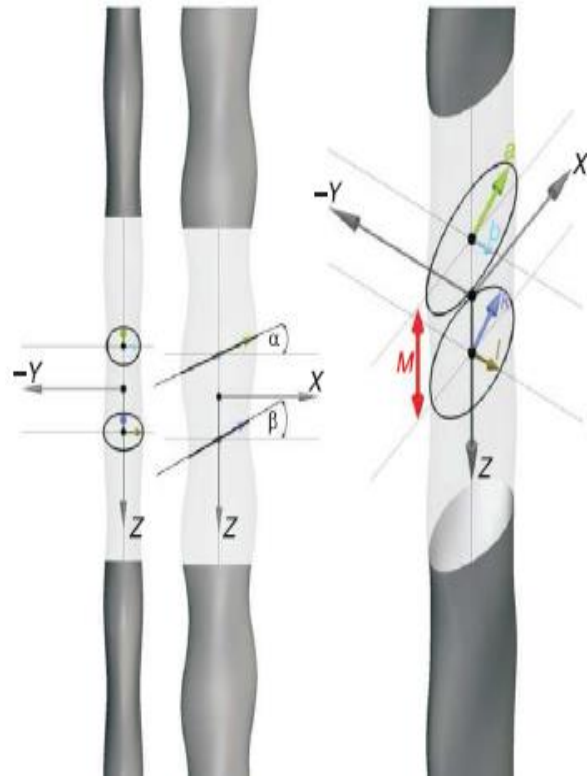
Whisker centroid, leading/trailing edge of major axis



Whisker leading and trailing edge distance from centroid

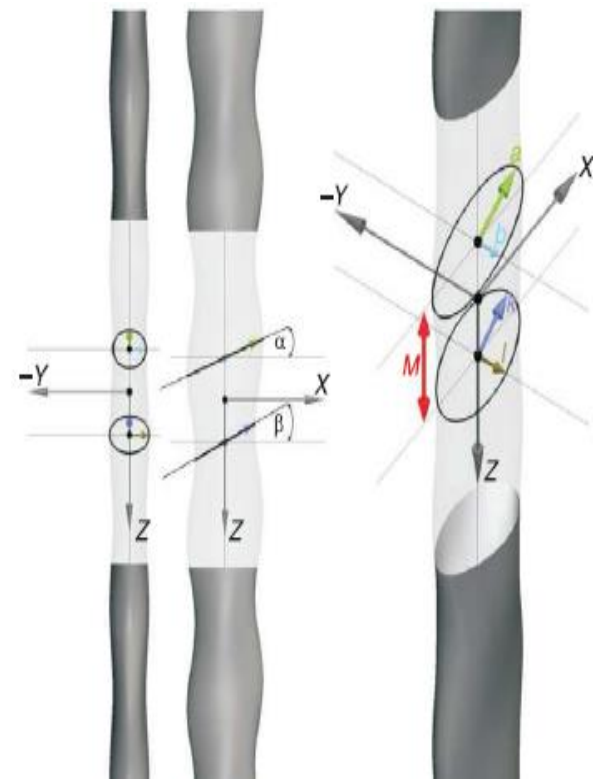
Elephant seal (es) whisker characterization

	Crest Angle α [Degree]	Crest Width a [mm]	Crest Wavelength Leading Edge M [mm]	Crest Wavelength Trailing Edge M [mm]	Trough Angle β [Degree]	Trough Width k [mm]	Trough Wavelength Leading Edge M [mm]	Trough Wavelength Trailing Edge M [mm]
es 3531	-33.840	1.792	4.467	4.265	-39.232	1.851	4.627	4.137
es 3546	-0.068	1.270	4.114	4.114	4.064	1.095	4.127	4.148
es 3645	-3.349	1.130	3.957	3.955	-0.979	0.981	3.941	3.922
es 3600	1.327	1.256	4.452	4.452	1.590	1.076	4.356	4.379
es 3600	-2.226	0.729	2.695	2.695	-4.322	0.580	2.747	2.747
es 3643	-26.522	1.721	4.470	4.197	-32.226	1.514	4.469	4.200
es 3546	-0.425	1.128	3.834	3.921	-3.801	0.996	3.961	3.973
es 3531	-2.161	1.358	4.712	4.616	-12.592	1.209	4.740	4.757
	9.559	1.265	4.360	4.230	-25.692	1.190	4.072	4.056
es 3531	10.912	1.143	4.168	4.260	3.833	1.057	4.504	3.760
es 3531	1.195	1.120	3.516	3.764	12.009	0.911	3.672	3.724
es 3527	-7.081	1.052	3.928	3.892	-21.572	0.989	4.168	3.812
es 3527	-4.849	0.906	3.418	3.326	-6.607	0.765	3.604	3.332
es 3628	0.390	1.285	4.344	4.516	11.604	1.065	4.348	4.264
es 3628	-0.138	1.225	4.298	4.228	1.437	1.033	4.404	3.948
Average	-3.818	1.225	4.049	4.029	-7.499	1.087	4.116	3.944
Stdev	11.767	0.268	0.521	0.490	15.608	0.295	0.501	0.464



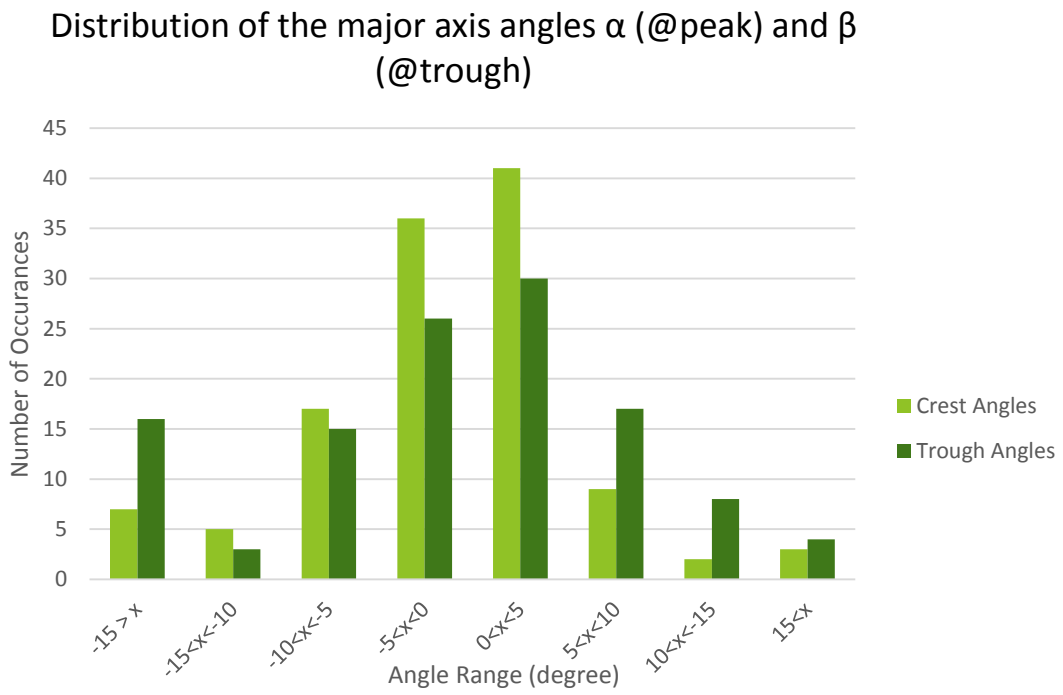
Harbor seal (hs) whisker characterization

	Crest Angle α [Degree]	Crest Width a [mm]	Crest Wavelength Leading Edge M [mm]	Crest Wavelength Trailing Edge M[mm]	Trough Angle β [Degree]	Trough Width k [mm]	Trough Wavelength Leading Edge M [mm]	Trough Wavelength Trailing Edge M [mm]
hs 2373	-0.348	1.258	3.813	3.824	0.060	0.942	3.792	3.816
hs 2372	-0.111	1.178	3.902	3.921	-2.490	0.923	3.952	3.976
hs 2357	4.155	0.750	2.718	2.711	5.187	0.623	2.747	2.768
hs 2347	-1.101	0.932	3.283	3.342	0.473	0.714	3.360	3.360
hs 2347	-0.330	1.197	4.021	4.034	1.862	1.031	3.991	3.970
hs 2357	0.675	1.115	3.333	3.328	1.142	0.873	3.387	3.375
hs 2372	2.222	1.255	4.182	4.173	2.882	0.990	4.275	4.262
hs 2373	-1.858	0.924	3.054	3.051	2.711	0.724	3.047	3.031
	-4.306	1.124	3.906	4.010	4.171	0.848	4.208	4.132
hs 2373	-6.477	0.994	3.276	3.648	-6.967	0.890	3.504	3.528
hs 2373	5.319	1.141	3.532	3.558	-6.891	0.947	3.616	3.676
Average	-0.196	1.079	3.547	3.600	0.195	0.864	3.625	3.627
Stdev	3.405	0.160	0.455	0.455	4.084	0.127	0.477	0.466



- Averaged twisting angle is not representative
- This angle was not considered in engineered wavy cylinder studies but may be important (Zhang et al. 2005)

Twisting angle distribution of whisker samples



- Averaged twisting angle is not representative
- This angle was not considered in engineered wavy cylinder studies but may be important (Zhang et al. 2015)

Engineered Whisker-like Models

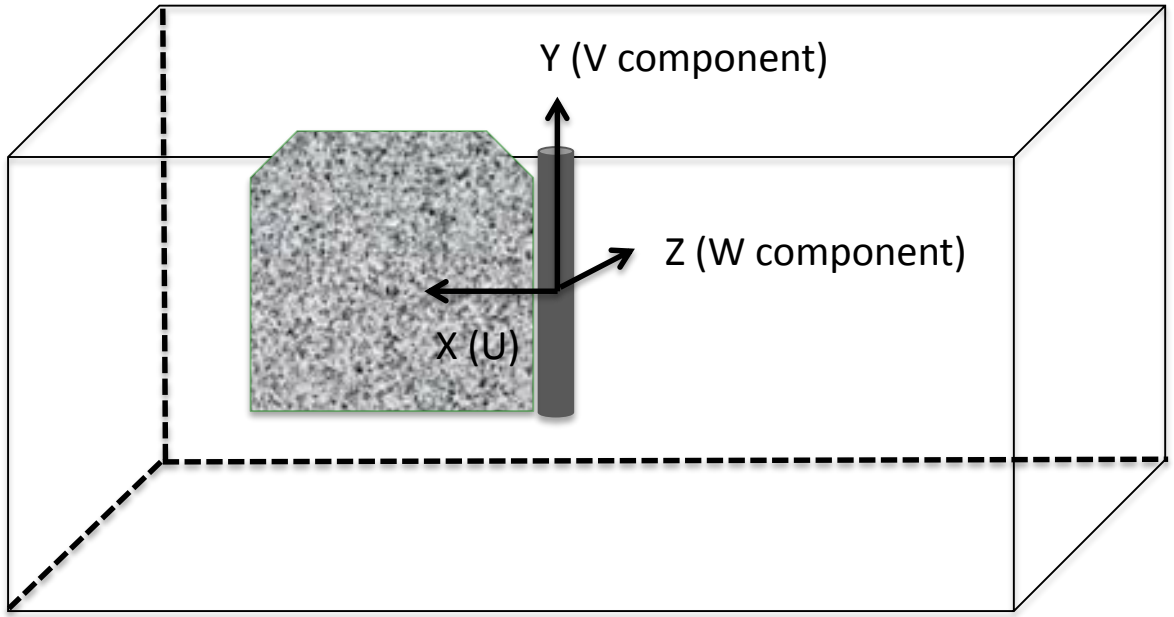
- scaled-up rigid models (8-10 times of the real whisker scale);
- varying the twisting angles α and β systematically

Test Cases	Alpha (deg.)	Beta (deg.)
B	0	0
2	5	5
D	15	15
4	5	– 5
5	+/– 5	+/– 5
6	*random*	*random*

Whisker-like models

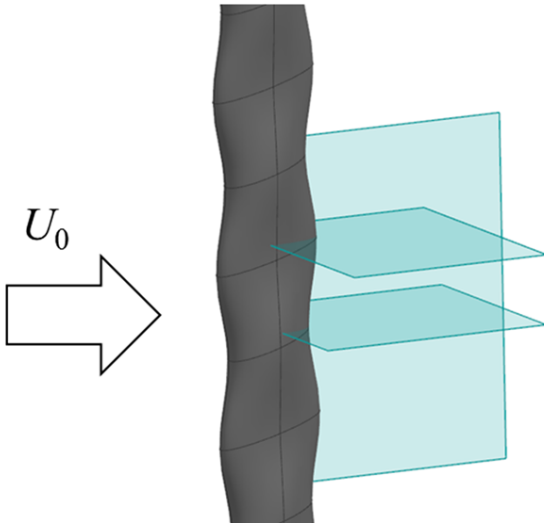
	a (mm)	b (mm)	k (mm)	l (mm)	M (mm)	D_m (mm)	M/D_m
Models	9.85	3.34	7.91	3.72	12.70	6.21	2.05

PIV measurements



Inflow
U = 0.1 m/s
I_u = 2-4 %

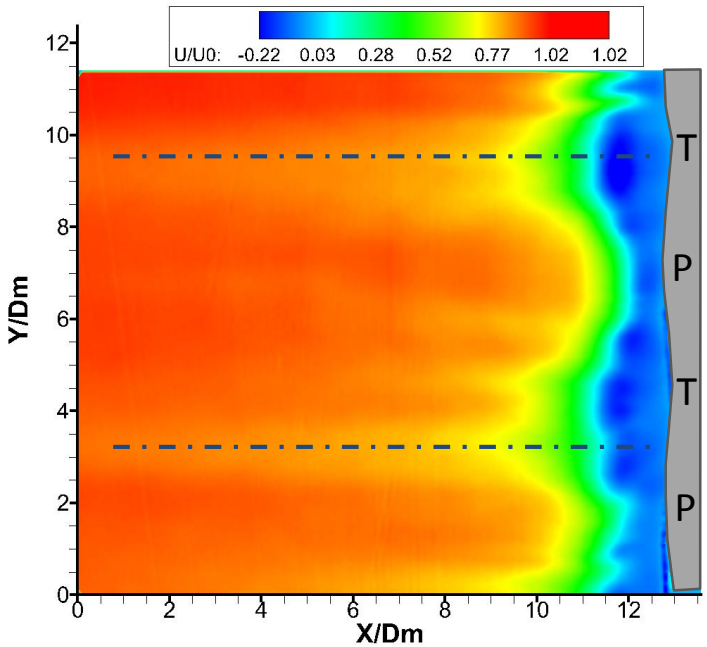
$Re = U_0 D_m / \nu = 680$



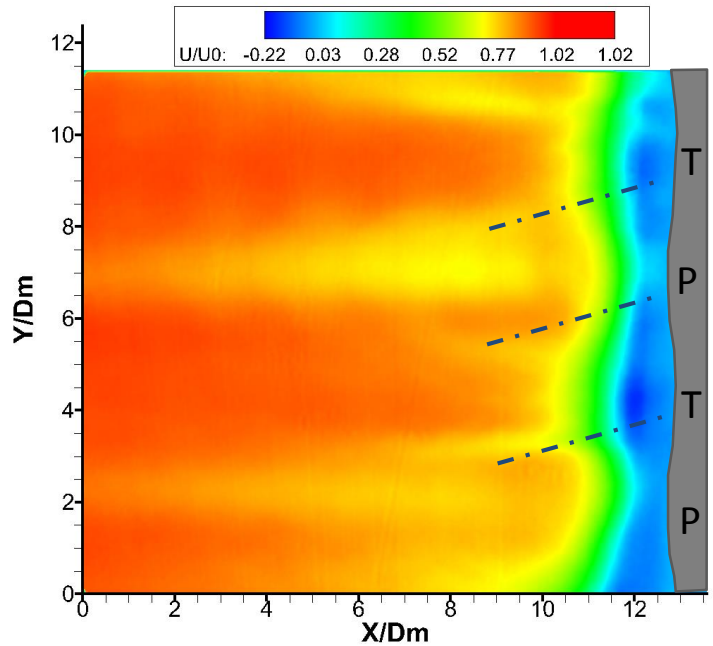
- 3D wake flow
- Vortex shedding behavior (f, St)

Sneak peek: Mean flow fields

Flow



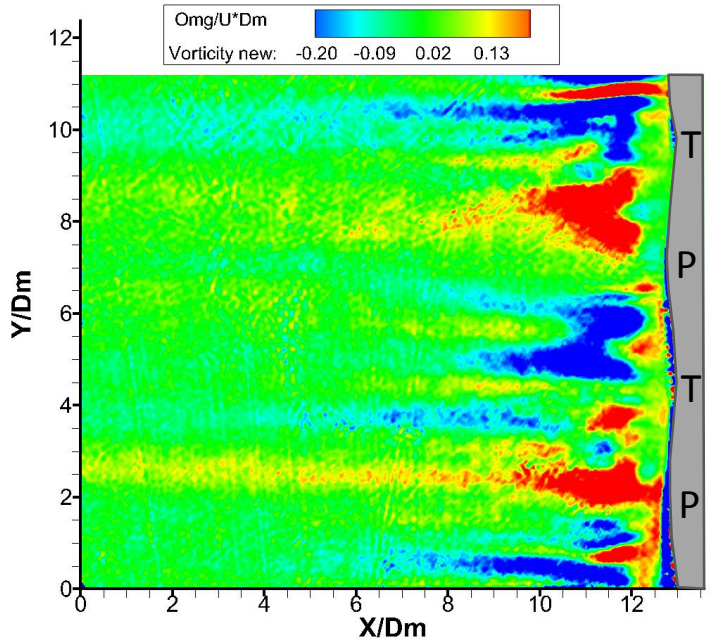
Whisker B
(α = β = 0 deg.)



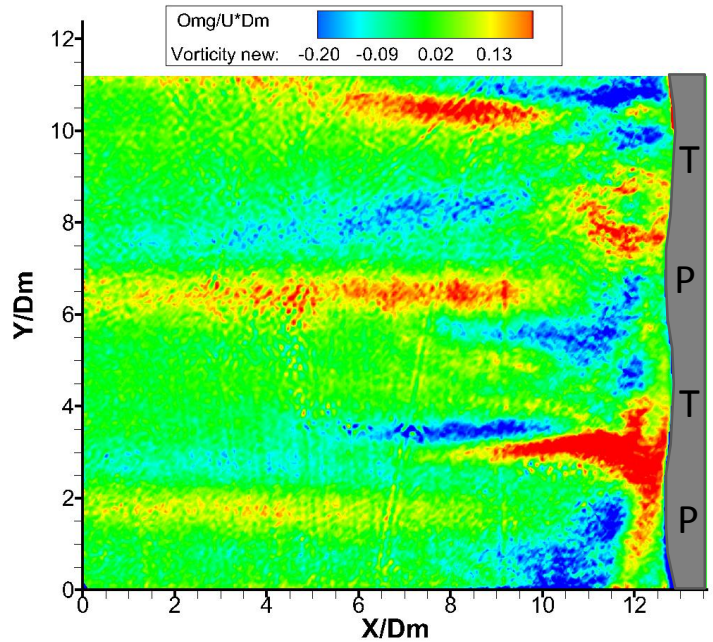
Whisker D
(α = β = 15 deg.)

Vorticity ω_z of mean flow

Flow

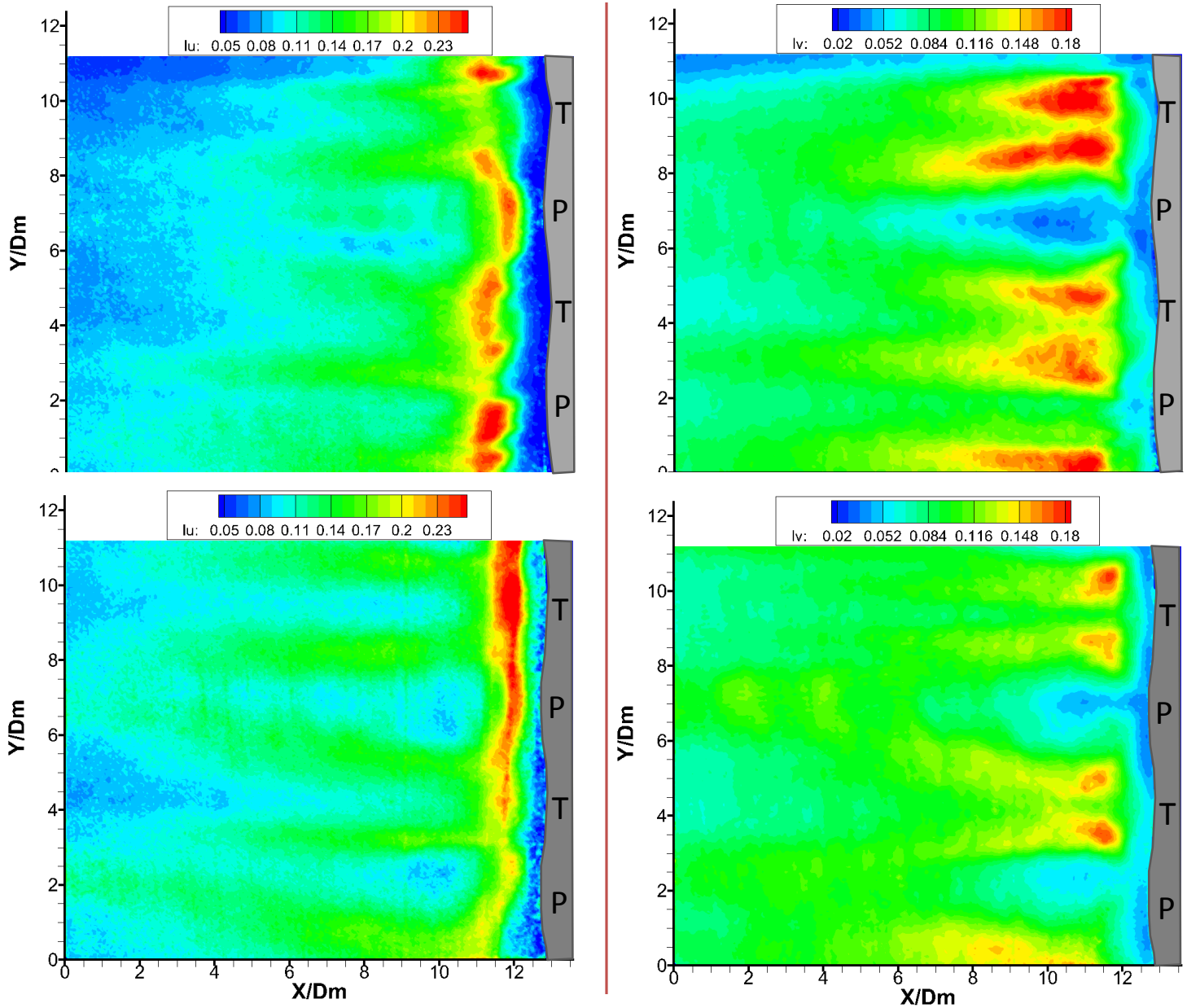


Whisker B
($\alpha = \beta = 0$ deg.)



Whisker D
($\alpha = \beta = 15$ deg.)

Turbulence intensities

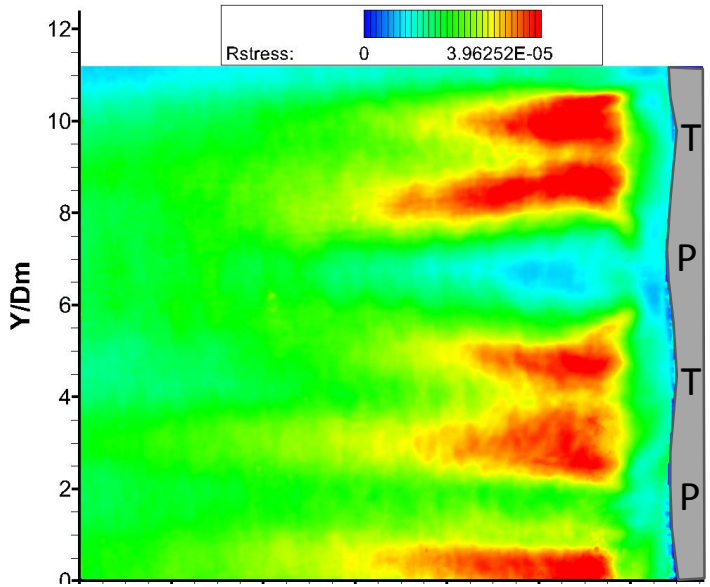


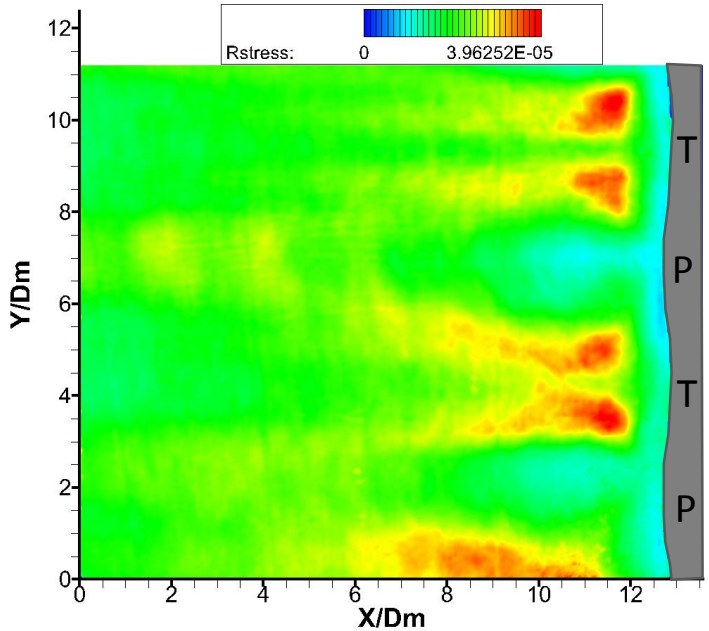
Flow

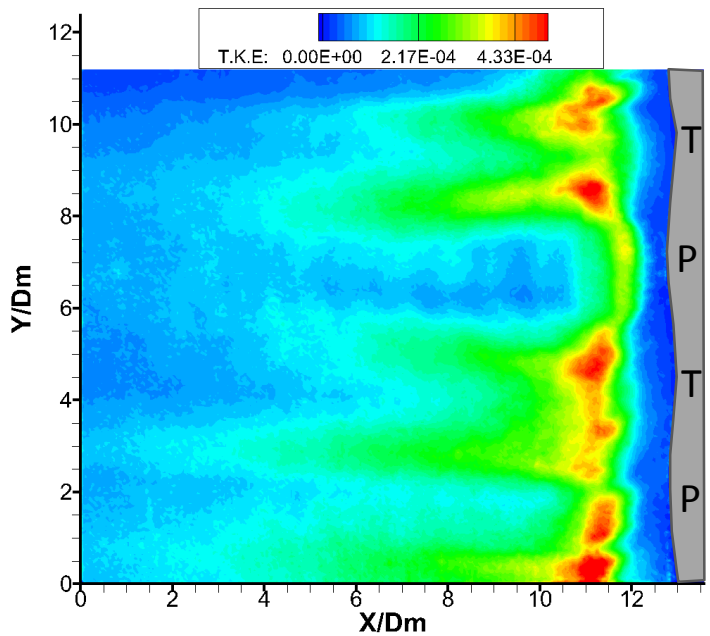
Whisker B
(α = β = 0 deg.)

Whisker D
(α = β = 15 deg.)

T.K.E. and RSS

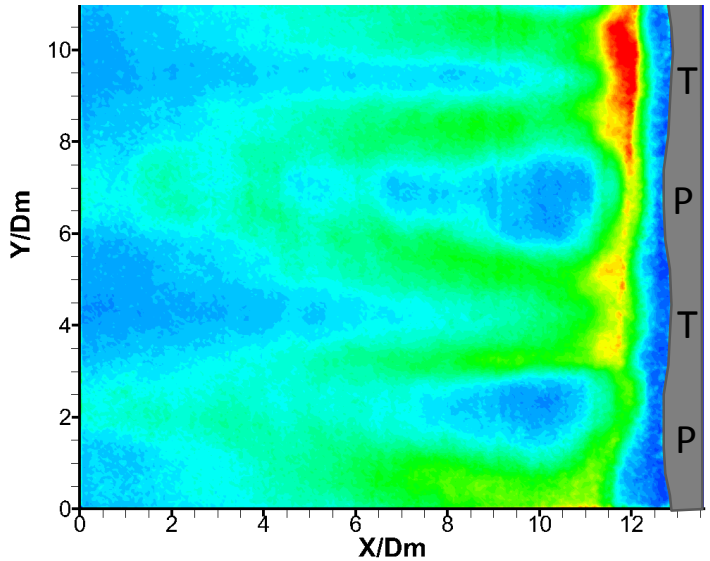






Flow

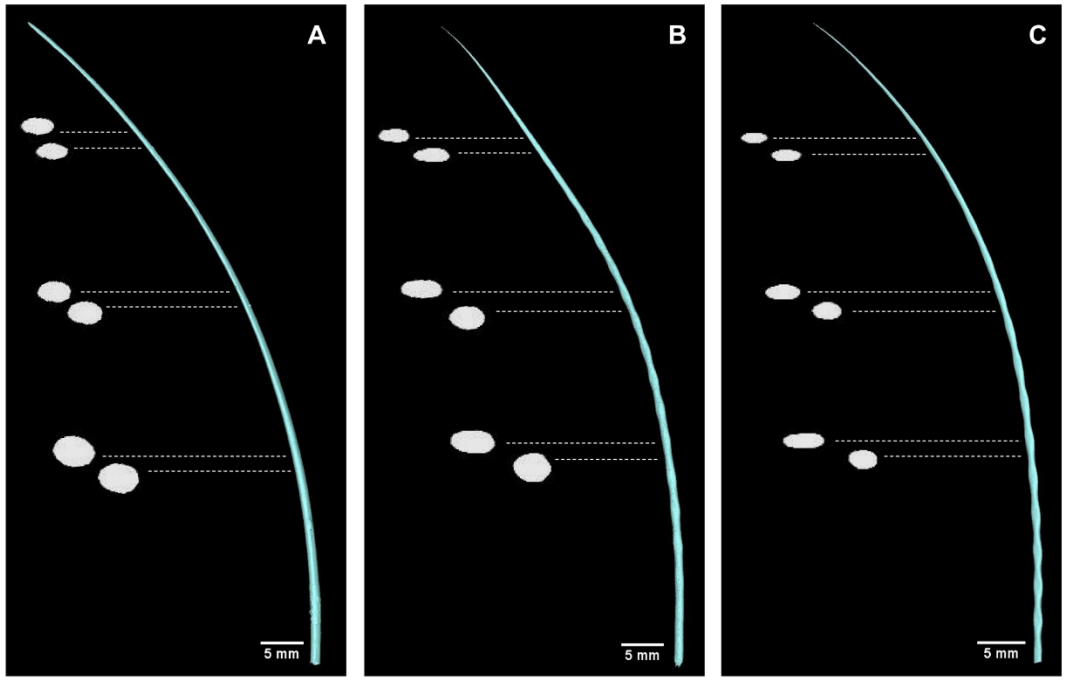
Whisker B
(α = β = 0 deg.)



Whisker D
(α = β = 15 deg.)

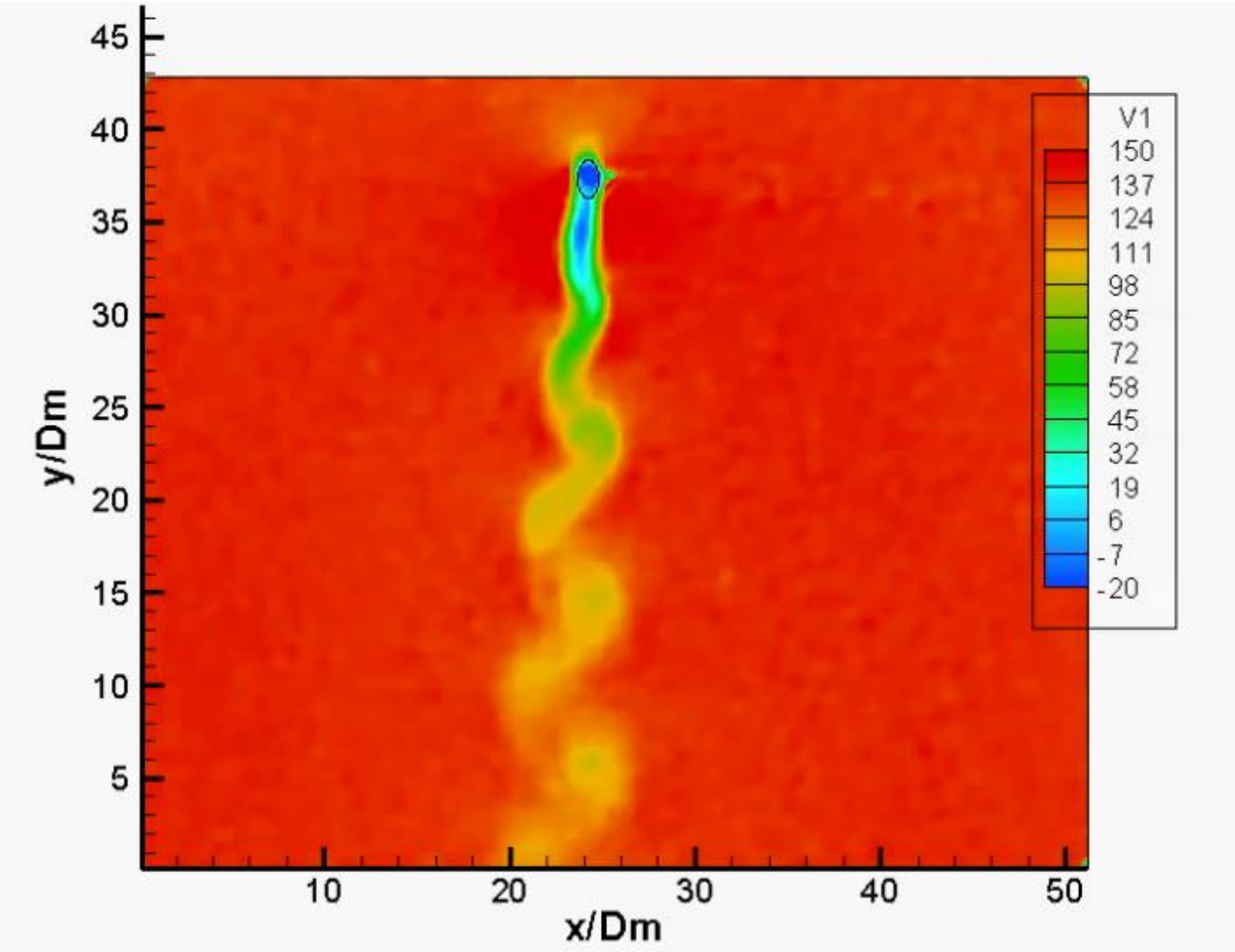
How about *real* whiskers?

- Real whisker: bending curvature and variation in size/twisting along the length
- Certain configuration in an array
- Response to upstream conditions (uniform inflow, wake flow)

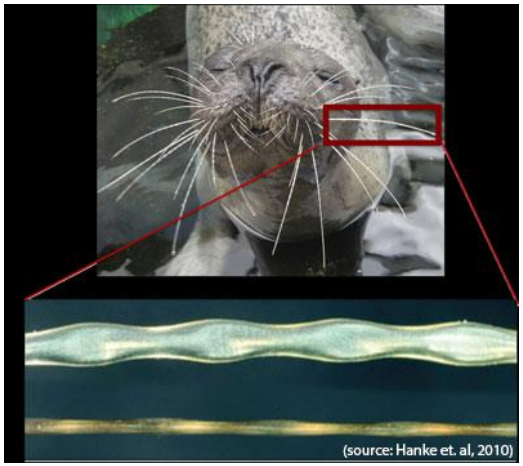


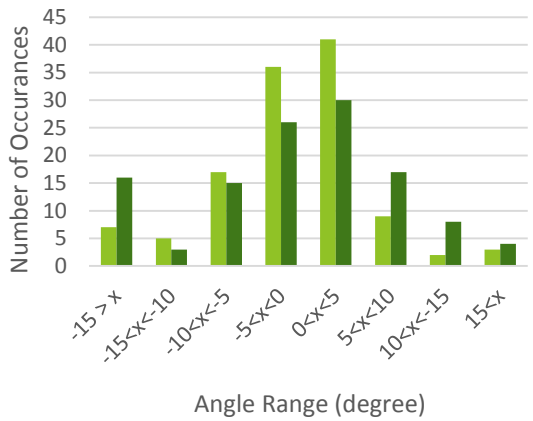
Murphy et al. 2013.

Wake and vortex shedding of a real whisker



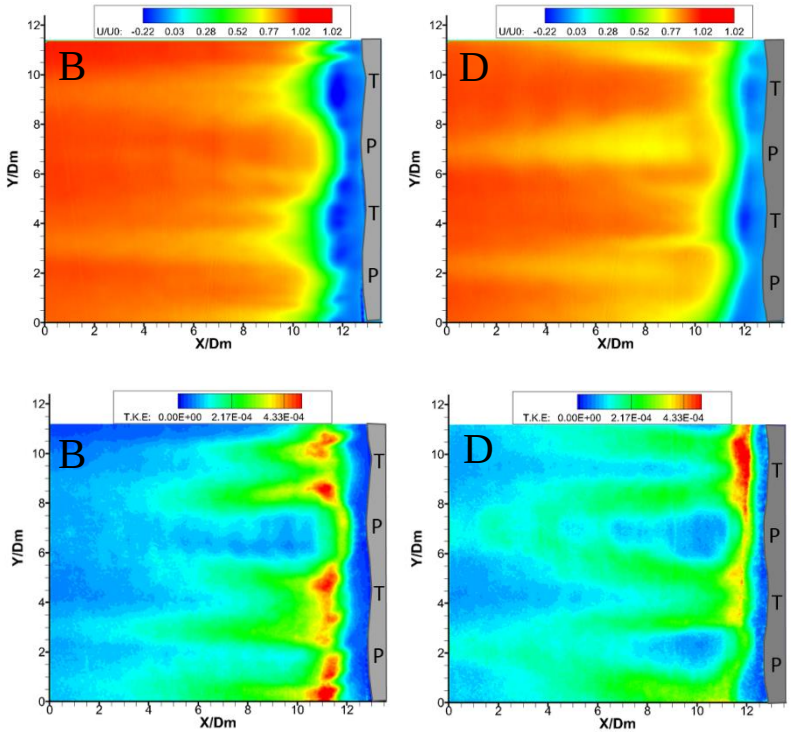
Summary and Outlook

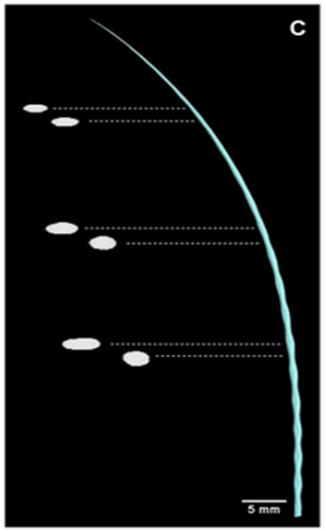




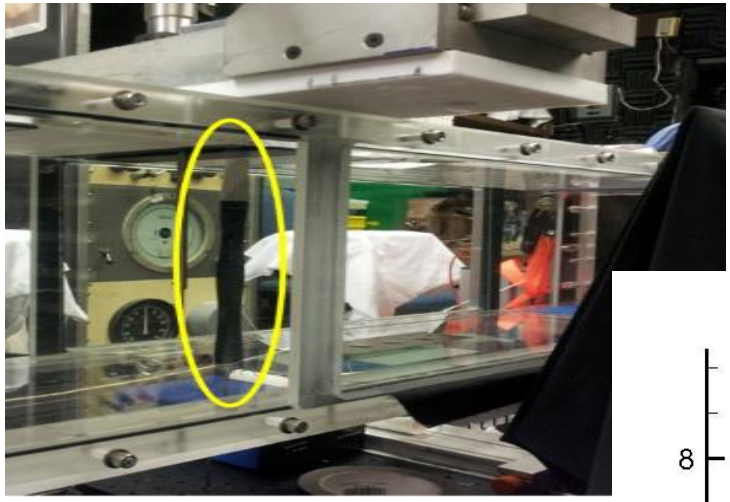
B: α=β= 0 deg.

D: α=β= 15 deg.





Wind-tunnel studies at NASA GRC



- High Re range;
- Hot-wire anemometer survey;
- PIV test;
- 2 cross-planes in the wake